Operational Experiences with the Petite Amateur Navy Satellite – PANSAT

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ABSTRACT

This paper provides an overview of PANSAT's on-orbit performance by discussing how the integration process, design decisions, and space environment have affected mission operations. PANSAT, in its third year of operation, is providing a large quantity of telemetry, some of which has been analyzed by officer students at the Naval Postgraduate School. Battery temperatures and charge cycles, EDAC errors as well as solar panel currents, are some of the telemetry data that were analyzed to gain insight about satellite performance.

PANSAT Program History

Launch

PANSAT was ejected into a 555-km (300nmi.) circular 28.5-degree inclined orbit on October 30 1998. A primary objective of this project was to provide the opportunity for officer students of the Naval Postgraduate School Space Systems Engineering and Space Systems Operations curricula to design and work with space flight hardware. In excess of 50 master's theses related to PANSAT have been published since the conceptual study in March 1989. In addition to providing a hands-on experience for students a second objective was to design a spread spectrum communications system for PANSAT using commercial-off-the-shelf components (COTS).

Status

PANSAT, which will complete its third year in orbit October 29 of 2001, is still operational and gathering housekeeping telemetry. During it's mission PANSAT's Nickel Cadmium (NiCd) batteries have cycled thousands of times, the Error Detection and Correction circuit (EDAC) has detected numerous bit flips in RAM. Software uploads have been completed for the purpose of testing improved battery charge algorithms. In addition, in certain instances software was uploaded to allow PANSAT to store short duration high-resolution telemetry data sets. To date no electronic subsystem has failed but both batteries are losing capacity and one battery has had two cells shorted temporarily.

Design

General Requirements

PANSAT was designed for a two-year mission life. The main mission design requirements were for PANSAT to provide a store-and forward digital communications system using direct sequence spread spectrum techniques and serve the amateur radio community by providing a store-and-forward service. The communications system operates in the UHF band with a center frequency of 436.5 MHz. Another design goal was to maximize reliability by implementing the satellite with redundant subsystems. The PANSAT subsystems are the Systems Controller (SC), Telemetry Multiplexer (TMUX), RF Modem, Transmit and Receive system, Electrical Power System (EPS), and batteries. PANSAT has two of every subsystem with the exception of the EPS. Despite the redundancy in the major subsystems PANSAT is a "single-string" design with several single-points-of-failure. Simplicity and cost were the primary factors in the approach to designing this satellite. Because PANSAT was designed as a tumbling satellite it was assumed that at some point the launch interface could fly facing into the sun. In this orientation the four bottom silicon solar panels would be shadowed by the launch interface. To ensure that some power generation would occur at this orientation, a GaAs panel was attached to the bottom face of the launch vehicle interface (LVI) generating 1.6 watts of power.

Attitude Control

In keeping with a simple design approach, PANSAT was designed with no attitude stabilization system. The Hitchhiker Ejection System (HES) employed for ejecting small satellites from the Shuttle cargo bay imparted a spin about PANSAT's main axis of approximately 1 rpm. From telemetry measurements it was possible to determine this spin rate and detect a nutation. Because PANSAT was designed as a tumbling satellite the thermal design was minimal and consists of only conductive materials placed between the batteries and equipment plate.

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Single Processor

Original requirements described a satellite with three processors, one processor each for the EPS, SC, and RF modem. However, average power available from the solar panels is 17.45 W, which, after subtracting losses due to battery charge/discharge inefficiencies and solar panel diodes, drops to 16.33 W. This is too small an amount of power to support a design with three processors. As a result PANSAT was redesigned to operate with one processor, an Intel M80C186XL. This processor runs the battery charge monitor – a software algorithm that controls the charge state and health of the NiCd batteries. In addition this processor gathers telemetry, generates data packets for sending and handles commands and software uploads received from the ground station. The SC processor operating at 5MHz performs all these operations.

Radiation, SEU's, EDAC and System Resets

The radiation environment for a LEO satellite is benign when considered from a total dose failure standpoint, since missions are generally too short and radiation levels too low for failures to occur in electronics components. The major radiation related hurdle to overcome when designing PANSAT was mitigating single event effects such as single event upsets (SEU), latchups (SEL), and burnout (SEB). Specifically, finding commercial components for which single event effects (SEE) information is available, was difficult. The approach was to determine for which components of the satellite SEEs would most likely create operational problems. The most susceptible component is the SC RAM. To protect the RAM from bit flips, an Error Detection and Correction (EDAC) system was designed to wash the RAM. This EDAC system can detect single and double bit errors and correct single bit errors. In the event that a double bit error occurs the SC software will purposely not reset a watchdog timer in the EPS subsystem so that after 1.5 minutes the EPS will power down the system controller with an uncorrectable error in RAM and power up the alternate system controller.

In general the selection of large scale integrated electronic components, often referred to as "glue logic," used for the EPS design, has been successful in prohibiting any latchups in the EPS. This is important since there is no method to reset the EPS if a latchup were to occur. Also, if a latchup were to occur in the communications bus – Peripheral Control Bus (PCB) – the battery charge monitor which controls battery charging and subsystem power by commanding the EPS, would be unable to carry out it's functions.

Batteries

Original design requirements defined a satellite with two 45 Wh batteries. One battery was to be used exclusively until it failed then the backup battery would be used. However, after more study it was determined that a single battery would encounter 11,860 cycles at a 10% depth of discharge (DOD) in a two-year mission, well above the expected service life of 5000 to 7000 cycles. [1] Employing two batteries in tandem reduced the number of battery cycles to two each day per battery. The method is to keep one battery online supplying power in eclipse and buffering communications to the ground station for a period of four orbits. After four orbits, which equates to a 40% DOD, the other battery, which has been charging over the same time period, is switched online and supplies power for the next four orbits. This way each battery operating in tandem only incurs 1460 cycles during a two year mission under ideal conditions. The expected service life of Sanyo Cadnica KR-4400D Nickel Cadmium batteries at a 40% DOD is between 2100 and 3700 cycles. A more detailed description of the EPS and battery design can be found here. [2]

Safety Measures

Battery Housing Design

Each battery is comprised of nine commercial-off-the-shelf (COTS) Sanyo Cadnica® NiCd cells. Cadnica cells have a pressure relief valve and therefore are not considered sealed by NASA safety standards. For this reason, a housing with a pressure relief valve was designed to contain any electrolyte leakage or generated gas. This was done even in light of the fact that Cadnica cells are considered "dry" cells and contain only two drops of electrolyte each.

To further reduce the risk of gas generation from electrolyte leakage, the interior of both battery housings were coated with Teflon®. Since gas may be generated when the batteries are over-charged, quartz wool was packed into the empty volume of each housing to reduce the volume of gas buildup should explosive gases accidentally be generated. Prior to integration into the spacecraft structure both batteries were leak-checked with helium and then purged with dry nitrogen. To guard against heat buildup in the case of an accidental short, a temperature cutout set to 55 degrees C was placed in the ground leg of each battery inside the housing.

The battery housing design as described above details the amount of work needed to satisfy NASA safety requirements. As a result this battery design that meets NASA manned space vehicle safety requirements

required hundreds of work-hours to design, in addition to hundreds of work-hours to build the 4 flight batteries. Building each battery took one work-week. [4] When designing a small satellite for launch from on the shuttle, it is wise to start the battery design early.

Mechanical Switches

NASA safety personnel at Goddard Space Flight Center (GSFC) worked with the Space Systems Academic Group to ensure a safe launch of the PANSAT. Beginning a year and a half before launch safety issues were addressed in the design of PANSAT. It was required that to be approved for launch, PANSAT would need three independent inhibits to prevent powering up while in the cargo bay. In addition, after ejection from the Hitchhiker canister, two inhibits needed to be in place to restrain PANSAT from transmitting while in general proximity of the shuttle. The three inhibits used in the cargo bay were mechanical switches in the solar panel power bus. Two switches were placed in the power leg and one in the ground leg of the solar panel power bus resulting in three independent inhibits. The batteries were discharged as the last step in the integration process to inhibit inadvertent transmissions at peak power. Once ejected, the batteries and mechanical switches could no longer be counted as inhibits. A timer in the RF system and the software served as two independent inhibits following separation.

Antenna Deployment

The PANSAT antenna design consists of four quarter-wave length beryllium copper elements, which are mounted at the top four corners of the satellite. See Figure 1 for an expanded diagram of the satellite structure. In the original design each antenna element would be attached to a Nichrome® wire by a nylon filament. After ejection the antennas would be deployed by switching power to heating elements, which would melt the nylon filament and deploy the antennas. NASA safety personnel ruled that this deployment method did not meet safety requirements. It was then decided to launch without a lid on the Hitchhiker canister since the antenna elements would be outside the canister and not be restricted by the canisters internal payload envelope. This decision was the cause of trouble during integration and the entire PANSAT mission.

Integration and Test

Test

With the exception of the batteries that were not thermally cycled, all electronic subsystems were thermal vacuum and vibration tested at the Naval Postgraduate School, Space Systems Academic Group

facilities. The satellite, once integrated into a Hitchhiker test canister, was then vibration tested as a unit at GSFC. Following the vibration test, a functional test was performed to verify PANSAT was functioning correctly. Safety requirements then dictated that each battery be discharged so that the inhibit requirement could be met. The process for discharging each battery required three solar panels be removed to access the battery housings so that a series of resistor packs could be placed across individual cells and discharge them in parallel. While removing one solar panel a screw with a broken head was discovered. The batteries were discharged according to plan and then the solar panels replaced. Within the week it was decided that because calibrated torque wrenches had not been used to tighten structural screws when the satellite was constructed, the entire team of engineers returned to GSFC and completely disassembled and replaced all fasteners in the satellite structure.

Bent Antennas

At the third NASA safety review, the final review before delivery of the payload, the antenna deployment method as described earlier in this paper was determined to be unreliable by NASA safety personnel. Issues with the design were twofold. Was it possible to attach a loop nylon filament to the antenna elements and around the heating element by either tying a knot or by epoxy such that it would hold during launch? NASA safety decided not to allow the deployment arrangement. However, the deployment method was to ensure that the antenna elements did not break the payload envelope. A modification to the Hitchhiker ejection system was proposed to alleviate this problem. The solution was to raise PANSAT on the Hitchhiker Ejection system so that the antennas would protrude over the top of the canister. However, when PANSAT was placed into the Hitchhiker test canister prior to vibration testing it was discovered that the antenna elements did not protrude over the top edge but rather broke the payload envelope and rested on the top rim of the canister. It was too late at this point to do anything other than bend the antenna elements. Later analysis showed that by bending the antennas the antenna pattern became exaggerated, deepening the nulls and increasing the peaks. As a result communications with PANSAT has been problematic at times.

Radiation Effects

EDAC Performance

As described earlier in this paper, one important component of the satellite necessary for increasing reliability is the Error Detection and Correction system, which is built around a radiation hardened ACS630MS
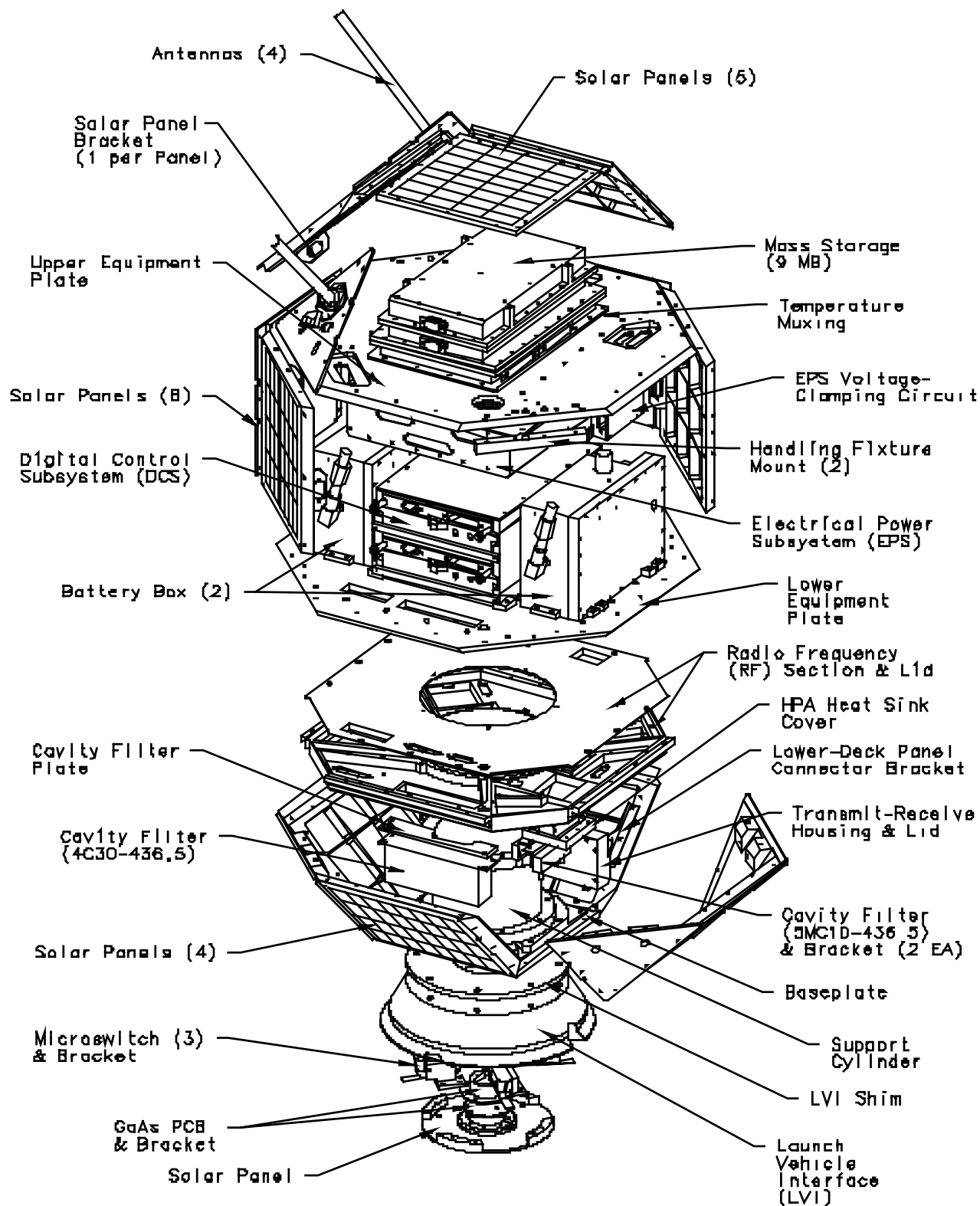
Figure 1 Pansat Expanded View

Labels in figure:

Antennas (4)

Solar Panels (5)

Solar Panel Bracket (1 per Panel)

Mass Storage (9 MB)

Upper Equipment Plate

Temperature Muxing

EPS Voltage-Clamping Circuit

Solar Panels (8)

Handling Fixture Mount (2)

Digital Control Subsystem (DCS)

Electrical Power Subsystem (EPS)

Battery Box (2)

Lower Equipment Plate

Radio Frequency (RF) Section & Lid

Cavity Filter Plate

HPA Heat Sink Cover

Lower-Deck Panel Connector Bracket

Cavity Filter (4C30-436.5)

Transmit-Receive Housing & Lid

Solar Panels (4)

Cavity Filter (3MC1D-436.5) & Bracket (2 EA)

Baseplate

Microswitch (3) & Bracket

Support Cylinder

LVI Shim

GaAs PCB & Bracket

Solar Panel

Launch Vehicle Interface (LVI)

EDAC controller. This controller implements a sequential state machine to generate the required control signals for the RAM and provides the necessary interface to isolate the RAM data bus from the local microprocessor bus. [5] Software is implemented in ROM to provide for a complete RAM memory wash every 4096 seconds (68.27 minutes). When a memory location is found to have a single bit error an interrupt is triggered that will record the date and time of service. While on average PANSAT experiences a single bit error per day, the maximum number of errors was four in a single day. [5]

It was decided to plot the EDAC error telemetry and verify if more errors occurred in the South Atlantic Anomaly region than on average over the other portions of PANSAT's orbit. However, the 4096 seconds it takes to perform a RAM wash equates to 2/3 of an orbit period making it impossible to locate the exact position of a bit error. An updated version of the PANSAT ROM software was written and uploaded. This version made a complete RAM wash possible in 136.5 seconds. With an orbital period of 5739 seconds, 136.5 seconds equates to 8.56 degrees or 10454 km. As a result, the average error in determining the location of an ECAC error is 516 km. Telemetry sets using the updated software yielded sixty-three data points and are plotted in Figure 2. Of the sixty-three data points plotted, approximately 90% fall within the area of the South Atlantic Anomaly. [5] [1†]

Radiation Effects

Analog electronic devices have no memory circuits such as latches and flip-flops, which may change state when hit by a radiation particle. Single event effects differ for these devices from the effects encountered by digital circuits. Most often the effect is a transient and there is evidence in PANSAT telemetry to suggest single event transients occur in the multiplexing circuitry of the EPS subsystem. This phenomenon has been detected in the battery cell voltage readings of battery B. The effect is to cause one cell voltage measurement to read high and another to read low such that a plot of these two cell voltages are mirror images of each other. The effect of this transient is negligible since the readings cancel each other and the battery charge monitor algorithm is unaffected. The effect can last from minutes to hours after which the readings return to normal. Figure 3 is a graph of PANSAT battery cell voltage telemetry, which shows the effect of a single event transient.

[1†] The South Atlantic Anomaly area is approximately –22.5º to –24.5º latitude and 312.5º to 317.5º east longitude.

Telemetry

Communications link

As described earlier in this paper PANSAT's antennas were bent to satisfy safety requirements. This in turn affected the antenna radiation pattern and reduced the amount of data that could be downloaded. Over the course of the mission, communications with the ground station was sometimes spotty sometimes very good. The quality of the signal during a single satellite pass could vary from good to bad as well. For many passes PANSAT was contacted just as it rose above a 10-degree elevation but no communications was possible during the highest portions of the pass. This supports the hypothesis that the bent antennas exaggerated the antenna pattern. The mission was affected in that only approximately 32% of the available telemetry was ever downloaded. [5] This left big gaps in the telemetry record and made it difficult to analyze the telemetry data. It also affected software uploads making it impossible to complete uploads sometimes for days at a time.

Battery performance [5]

To evaluate battery performance it is important to count the number of cycles each battery experiences. Using the number of cycles in conjunction with battery cell voltage and battery current charge and discharge telemetry general trends in a battery's health may be inferred. However, problems with telemetry download that were mentioned earlier in this paper will limit the certainty with which conclusions may be drawn.

The first task in evaluating battery performance was to count the number of cycles each battery experienced in its first two years of the mission. When this process was begun several problems surfaced that could affect the accuracy of the cycle count. Software which was written to count the transitions of charge current from the charge to discharge state, had to be written so as not to count false charge cycles as a result of noise inherent in the measurement system. The telemetry processing software was run on all available telemetry files for the first two years and 5 months of the mission using thresholds of 100 mA and 200 mA for the battery currents and the result averaged to arrive at an estimate on the lower bounds of cycles per battery. Battery A was estimated to have 1338 cycles and battery B 1067 cycles. The difference in the two may partially be explained by the way in which the battery charge monitor – the algorithm that controls battery charge state – operates. Whenever a SC reset occurs, one of the first steps taken is to read from the telemetry files a satellite state history. From this history the battery charge state may be determined. However, on occasion the SC is not able to determine battery charge state and
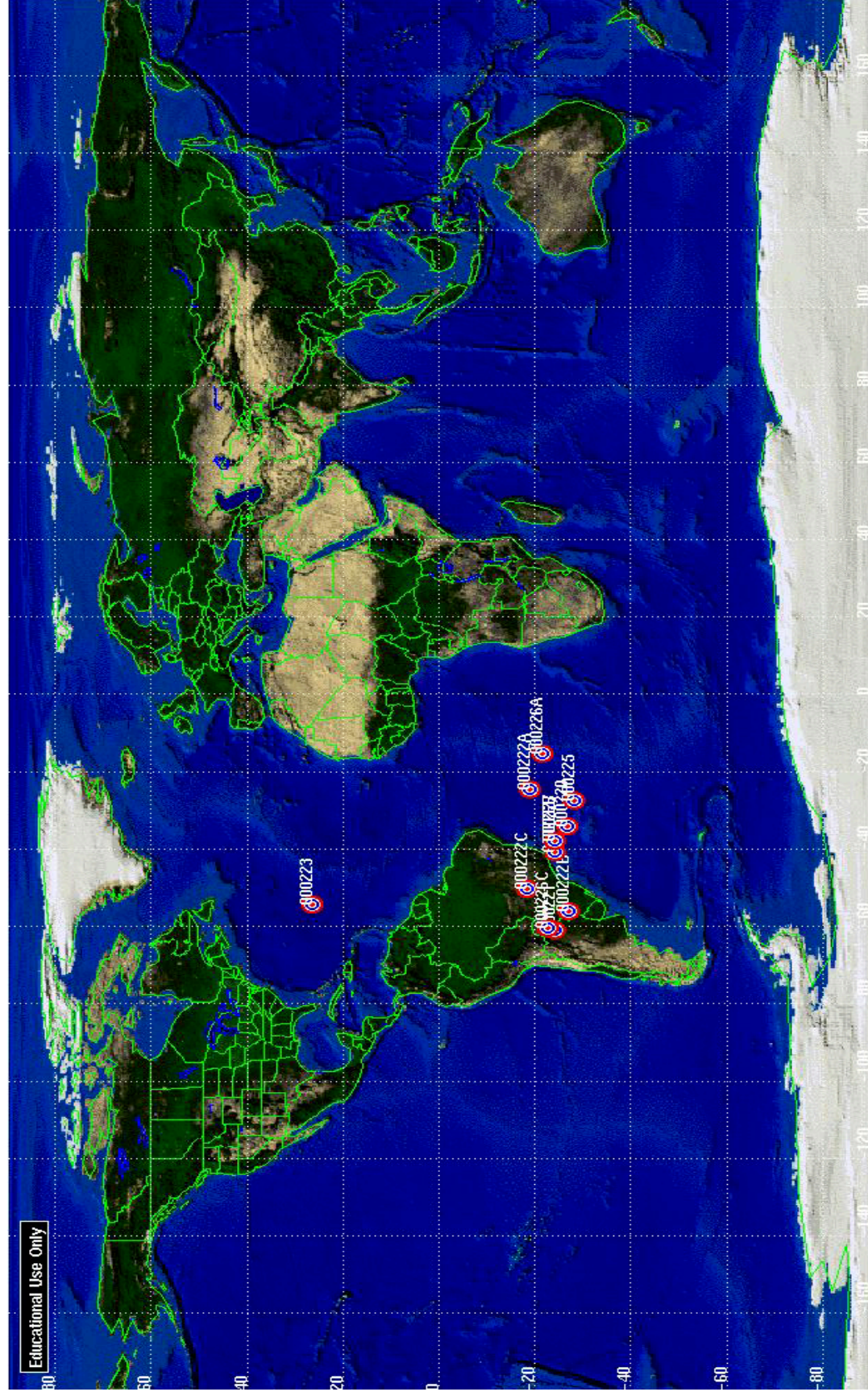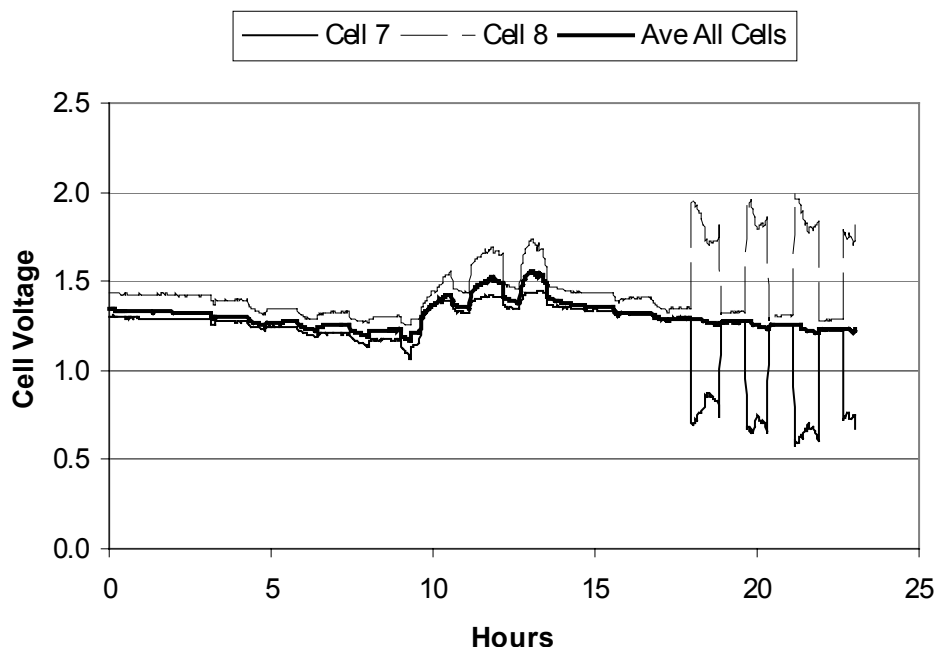
Figure 2. EDAC Errors February 2000

Figure 3. Single Event Effects on Telemetry Measurement System

proceeds to charge battery A as if the satellite had just been launched. Since the battery charge algorithm assumes that both batteries are discharged at launch it proceeds to charge battery A leaving it on during eclipse as well because it assumes battery B is discharged. In effect battery A in this situation can be cycled as much as 16 times – the number of orbits it takes to charge a PANSAT battery from a discharged state. As a result many more cycles occurred on battery A during the mission.

One indicator a battery is wearing out is an increase in the internal series resistance of its cells. To find evidence of this, telemetry files were investigated for those periods of time where the battery charge current, voltage and battery charge state is similar. Each battery has temperature sensors located on all cells. If the internal resistance of each cell increases as it ages, an increase in the average temperature during an overcharge cycle would increase over the course of the mission. Comparison of the averaged battery cell temperatures from the first half of the mission to those in the second half showed an increase for both batteries. Battery A temperature sensor readings increased an average of 0.435 degrees C and the average increase for battery B sensor readings was 2.02 degrees C. The large difference between the value for battery A and B

most likely is due to cell 7 of battery B having shorted in March of 2001.

The temperature environment of both batteries was investigated since long-term exposure to elevated temperatures can degrade battery cell components. Over the period of time investigated, the highest temperature measured was 38 degrees C. This was during the initial phase of the failure of cell 7 of battery B. The majority of temperature readings for each battery were between 5 degrees C and 20 degrees C with a minimum of –3 degrees C. Average temperature readings for both batteries were 10 degrees C. This leads to the assumption that the temperature environment has not played a part in the batteries wearing out.

Another indication of battery cell wear-out is the decrease in the average cell rest voltage after being charged. This effect is related to an increase in the internal series resistance in a cell. As a cell's internal series resistance increases, the useful cell voltage drops. The average no-load cell voltage for Battery A decreased over the period investigated by 0.07 Volts and the average battery no-load cell voltage for battery B decreased by 0.09 V. Further indication that wear-out is occurring for both batteries.

The EPS was designed without any current charge regulation and can be referred to as a battery-dominated design. A battery-dominated bus has its voltage regulated by the batteries whenever one is being charged. In addition each battery is connected to the solar panel power bus without any charge current regulation. That is, each battery will take as much current as can be supplied by the solar panels. The reason for this design is due to the small amount of power available to the satellite. A charge regulation scheme would further reduce the average available power. A quick charge rate for a standard charge NiCd cell, like the ones used in PANSAT, is between 0.2C and 0.33C. Actual charge rates for PANSAT's batteries at times approached 0.41C. For most of the charge cycle charge rates were near 0.25C. In comparison a standard charge rate is 0.05-0.01C. It is possible that the high charge rates experienced by these batteries have accelerated wear-out. During the design phase of PANSAT the use of larger cells was contemplated, however, internal volume restrictions precluded using F size cells as opposed to D size cells used. [7]

Solar Panel Current Sensors

Investigation of PANSAT's attitude dynamics was undertaken by analyzing telemetry measurements from the eight PANSAT solar panels instrumented with current sensors. An attempt was made to verify the roll rate imparted on PANSAT by the Hitchhiker ejection system as measured from a video recording of PANSAT's ejection from the Shuttle. Typically telemetry points are stored at two-minute intervals however, to achieve finer resolution in the telemetry set an updated version of PANSAT's ROM software was uploaded so that for short periods of time PANSAT could be commanded to store telemetry at 5-second intervals. A Matlab® program was written to graphically display PANSAT's orientation with respect to the sun based on dynamic modeling equations and the current sensor telemetry readings. Results from analyzing this finer resolution telemetry set were inconclusive in verifying PANSAT's roll-rate as the Matlab model was unable to display a smooth rotation of the satellite model. The inability to verify the roll-rate is a result of the 5 second resolution not being fine enough. However, with one processor handling all satellite operations, 5 seconds is the shortest time between telemetry set measurements PANSAT can gather.

Conclusions

PANSAT is the first autonomous spacecraft developed at the Naval Postgraduate School. During the design and operations phases a number of challenges were overcome. Lessons learned during this mission will benefit PANSAT's follow-on project Although PANSAT was not able to function as a spread spectrum store-and-forward satellite, other areas of the design were validated and PANSAT continues to function with only one temporary failure – a shorted battery cell. Finally, the inclusion of COTS components in PANSAT's design proves that a low-cost, single-string, satellite can be built by students and operated reliably as a "space lab in the sky".

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Biography

Ron Phelps is a graduate of the University of Kansas with bachelor's degrees in Electrical Engineering and Computer Science. He has spent the past dozen years working with the fine students who represent the many U.S. Armed Services in his capacity as a member of the Space Systems Academic Group of the Naval Postgraduate School.